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P/2006 VW$_{139}$: A Main-Belt Comet Born in an Asteroid Collision?

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ABSTRACT
In this paper we apply different methods to examine the possibility that a small group of 24 asteroids dynamically linked to main-belt comet P/2006 VW$_{139}$, recently discovered by the Pan-STARRS1 survey telescope, shares a common physical origin. By applying the Hierarchical Clustering and Backward Integration methods, we find strong evidence that 11 of these asteroids form a sub-group which likely originated in a recent collision event, and that this group includes P/2006 VW$_{139}$. The objects not found to be part of the 11-member sub-group, which we designate as the P/2006 VW$_{139}$ family, were either found to be dynamically unstable, or these are likely interlopers which should be expected due to the close proximity of the Themis family. As we demonstrated, statistical significance of P/2006 VW$_{139}$ family is $> 99\%$. We determine the age of the family to be 7.5 ± 0.3 Myr, and estimate the diameter of the parent body to be ~ 11 km. Results show that the family is produced by an impact which can be best characterized as a transition from catastrophic to cratering regime. The dynamical environment of this family is studied as well, including the identification of the most influential mean motion and secular resonances in the region. Our findings make P/2006 VW$_{139}$ now the second main-belt comet to be dynamically associated with a young asteroid family, a fact with important implications for the origin and activation mechanism of such objects.

Key words: comets: general, comets: individual: P/2006 VW$_{139}$, minor planets, asteroids: general, asteroids: individual: 300163

1 INTRODUCTION

Main belt comets (MBCs) are objects that are dynamically indistinguishable from main belt asteroids, but which exhibit comet-like activity due to the sublimation of volatile ice (Hsieh & Jewitt 2006; Bertini 2011). To date, six such objects have been discovered (Hsieh et al. 2012b). MBCs are important because they represent a new reservoir of comets in the Solar system, and may give insights into the role of main-belt objects in the primordial delivery of water to the Earth as well as provide constraints on the composition of the protosolar disk.

Dynamical simulations performed by Fernández, Gallardo, & Brunini (2002) show that it is unlikely that present-day objects with main-belt orbits originated in the Kuiper Belt, assuming the current configuration of the major planets. This indicates that MBCs are likely native to the main asteroid belt. Still, Levison et al. (2009) show that during the early violent dynamical evolution of giant planet orbits, as required by the so-called Nice model (Tsiganis et al. 2005; Morbidelli et al. 2005; Gomes et al. 2005), some icy trans-Neptunian bodies may have been implanted in the asteroid belt. It is expected that most of these objects are located in the outer belt, but they might be found anywhere with semi-major axes larger than about 2.6 au.

Numerical simulations performed to assess the dynamical stability of MBCs suggest that the orbits of the currently known objects are stable, indicating that they are likely native to their current locations (Haghighipour 2009; Hsieh et al. 2012a,b). The only exception is P/2008 R1 (Garradd), which appears to be dynamically unstable (Jewitt, Yang, & Haghighipour 2009). These simulations did not take into account non-gravitational effects (e.g., the Yarkovsky effect), however, that may play an important role in the long-term stability of the MBCs.

Wherever MBCs originate from, their activity, although still not reliably understood, is likely triggered by the impact-excavation of subsurface ice (Hsieh, Jewitt, & Fernández 2004; Jewitt 2012) because completely exposed surface ice is unstable against sublimation at their heliocentric distances over Gyr time-scales. According to Hsieh (2009) and Capria et al. (2012), this hypothesis is in reasonable agreement with the present-day impact frequency in the main belt.

Thermal modelling by Schorghofer (2008) and Prialnik & Rosenberg (2009) shows that buried ice on a main-belt comet can in fact survive over the life of the solar system. However, while thermal devolatization may not preclude the existence of present-day ice (and therefore MBCs) in the main asteroid

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belt, there is the additional problem of collisional devolatization. Each time an impact triggers activity in a MBC by exposing a small amount of subsurface ice to direct solar heating, that particular area of the surface is effectively devolatilized once that ice has sublimated away. Using estimates of the active areas required to produce the activity observed for MBCs, Hsieh (2009) determined that the observed activity was most likely triggered by approximately metre-sized impactors. Using work by Cheng (2004) and Bottke et al. (2005b), it was then estimated that impacts by objects of this size in the main belt should occur roughly every 10^4 yrs. Over Gyr time-scales, the cumulative effect of such impacts could be to devolatilize a significant portion of the surface of an ice-bearing asteroid. More deeply buried ice could persist, safe from both thermal and collisional depletion, but would also therefore be inaccessible by activity-triggering impacts. Such asteroids would then be just as unlikely to exhibit activity in the present day and be identified as MBCs as other non-ice-bearing asteroids.

Because of these reasons, it is important to understand the dynamical environment of each MBC and any possible links to collisionally-formed asteroid families. Asteroid families are believed to originate in the catastrophic disruption of large asteroids (e.g. Zappalà et al. 2002), and are a fascinating and challenging subject in themselves. A few tens of families have been discovered to date across the main belt (e.g. Zappalà et al. 1995; Mothé-Diniz, Roig, & Carvano 2005), providing insights into the collisional history of the main belt (e.g., Marzari, Farinella, & Davis 1999; Bottke et al. 2005a), disruption events over a size range inaccessible to laboratory experiments (e.g., Michel, Benz, & Richardson 2003; Durda et al. 2007), the mineralogical structure of their parent bodies (e.g., Cellino et al. 2002), and many other subjects.

Previous analyses show that three of the six currently known MBCs (133P/Elst-Pizarro, 176P/LINEAR, and P/2006 VW_{139}) are associated with the large and old Themis family (Hsieh & Jewitt 2006; Hsieh et al. 2012b), which is thought to have formed from the catastrophic disruption of a ∼400 km parent body 2.5 ± 1.0 Gyr ago (Nesvorný et al. 2003). Additionally, a fourth MBC (238P/Read) is close to the Themis family in orbital element phase space, and may have once belonged to the family (Haghighipour 2009). More significantly, 133P has been found to additionally belong to the small and young Beagle family, which is thought to have formed less than 10 Myr ago (Nesvorný et al. 2008). This finding is significant because, using the devolatization rate derived by Hsieh (2009), if one assumes 133P is a primordial member of the Themis family, placing its age at ∼2.5 Gyr, less than 10 per cent of 133P's surface would be expected to be unaffected by impacts by the present day. In contrast, 99 per cent of 133P's surface would be expected to remain unimpacted if the object is assumed to only be 10 Myr old (i.e., the age of the Beagle family). This possible link to young asteroid families is supported by the finding by Hsieh et al. (2012a) that P/2010 R2 (La Sagra) belongs to a small cluster that may have a common collisional origin.

Comet-like activity in main-belt asteroid (300163) 2006 VW_{139} was discovered by the Pan-STARRS1 survey telescope on Haleakala in Hawaii on 2011 November 5 (Hsieh et al. 2011), with preliminary analysis of its activity (Hsieh et al. 2012b) showing that it is likely to be a genuine comet (i.e., exhibiting activity due to sublimation), rather than a disrupted asteroid (i.e., whose activity is due to a recent impact) such as P/2010 A2 (LINEAR) (e.g., Jewitt et al. 2010; Snodgrass et al. 2010) and (596) Scheila (Jewitt et al. 2011; Bodewits et al. 2011). (Hsieh et al. 2012b) also

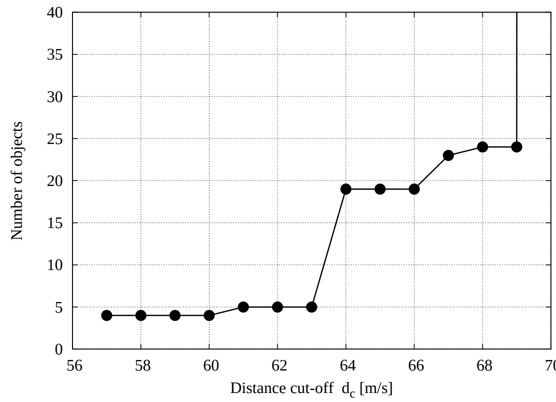

Figure 1. Number of asteroids associated with P/2006 VW_{139} as a function of cut-off distance (in velocity space), expressed in m s^{-1}. Two critical cut-off distance values are (i) 64 m s^{-1} when the number of dynamically associated objects increases significantly, and (ii) 70 m s^{-1} when the group around P/2006 VW_{139} merges with the Themis family. A potential sub-family within the Themis family is reasonably well defined in between these two critical values.

examined P/2006 VW_{139}'s possible links to dynamical asteroid families and found that it is dynamically associated with the Themis family, but that it may also belong to a smaller sub-group that could represent a new previously-unidentified young asteroid family.

In this paper, we conduct a detailed investigation into whether objects dynamically linked with P/2006 VW_{139} in fact have a common physical origin. First, we identify members of the group using the Hierarchical Clustering Method (HCM). Then we use the Backward Integration Method (BIM; Nesvorný et al. 2002a) in order to further test the reliability of the group and to estimate its age. Finally, we analyse the characteristics of this newly discovered family in greater detail.

2 LINKING P/2006 VW_{139} TO DYNAMICAL FAMILIES

We start our investigation by identifying the objects that are dynamically associated with P/2006 VW_{139}. The identification of asteroid families is usually done in proper orbital element space using proper semi-major axes (a_p), proper eccentricities (e_p) and sines of proper inclination ($\sin(i_p)$). For this analysis, we applied the HCM (Zappalà et al. 1990, 1994) to analytically-determined proper orbital elements (Milani & Knežević 1990, 1994) available at the *AstDys* web page[1], where we obtained elements for 398,841 asteroids (as of January 2012).

The results obtained by the HCM are the same as those obtained by Hsieh et al. (2012b), although here we use an updated proper element catalogue. Fig. 1 shows the number of asteroids dynamically associated with P/2006 VW_{139} as a function of the cut-off distance, d_c (in velocity space), the standard metric in the HCM. An intriguing sub-grouping appears at $d_c > 63$ m s^{-1} before then merging with the Themis family at $d_c = 70$ m s^{-1}. A complete list of asteroids that belong to this group is given in Table 1. Assuming that a cut-off value of $d_c = 70$ m s^{-1} used by Nesvorny (2010) to characterize the Themis family is still appropriate, the sub-group around P/2006 VW_{139} is formally a part of this family. However, the latter result should be interpreted with some caution because the

[1] http://hamilton.dm.unipi.it/astdys/index.php?pc=5

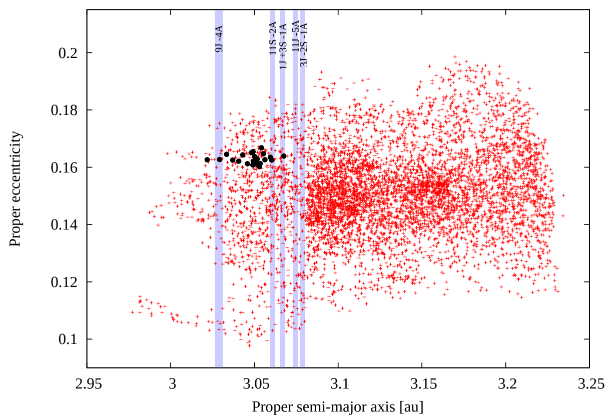

Figure 2. The distribution of the members of Themis family (small crosses) and the sub-group around P/2006 VW$_{139}$ (filled circles) in the (a_p,e_p) plane. The most notable two- and three-body mean motion resonances located close to P/2006 VW$_{139}$ group are marked as vertical dashed areas.

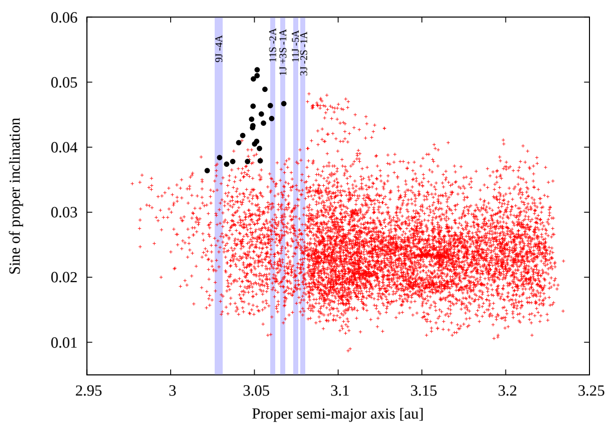

Figure 3. The same as in Fig. 2, but in the (a_p,sin(i_p)) plane. Note that group around P/2006 VW$_{139}$ is located on the edge of the Themis family.

group occupies the outskirts of the Themis family. Also, one should bear in mind that the cut-off value appropriate for characterizing an asteroid family tends to decrease as the number of known asteroids increases because the density of background objects becomes higher. Consequently, the appropriate value of d_c for the Themis family may be slightly smaller today than at the time of Nesvorny (2010) work. This is supported by the fact that list of the Themis family members produced by Nesvorny (2010) does not include the asteroids from P/2006 VW$_{139}$ group, although most of these objects were known at that time.

On the other hand, as can be seen in Figs. 2 and 3, the P/2006 VW$_{139}$ group is separated from the main part of Themis family by several two- and three-body[2] mean motion resonances (MMRs) and actually may be a real part of the Themis family simply separated by the MMRs.

To visualize the structure of the whole Themis family, we generate a stalactite diagram for the population of 6374 family members (Fig. 4). This type of diagram is extensively used in other family identification papers (e.g., Zappalà et al. 1990, 1994, 1995;

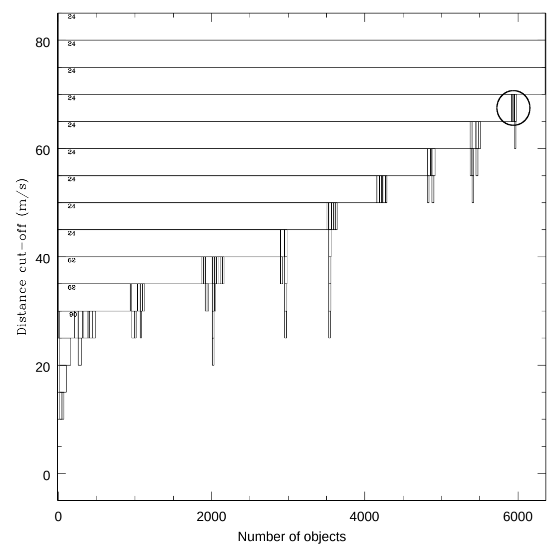

Figure 4. The stalactite diagram for 6374 Themis family members. Only the groups with at least N_{crit} = 19 members are shown. Note that P/2006 VW$_{139}$ group is visible only in the one step, at 65 m s^{-1} (its location is emphasised by the circle).

Novaković, Cellino, & Knežević 2011), and is a highly effective means of visually displaying the structure of a given region. Here, however, we have an opposite example: a group, which we show later is likely real, is visible only in the one step used in the diagram, and would not be considered a family based on standard criteria for family identification. This situation is a good illustration of the limitation imposed to this approach in the region occupied by large and dense asteroid families such as Themis.

The density of background objects in this region is high, and it is exceptionally difficult to separate nearby families due to the phenomenon of chaining.[3] Because of that, we are unfortunately unable to draw conclusive result whether this group belongs to the Themis family or not. However, this problem does not affect our further investigation of the P/2006 VW$_{139}$ group.

3 THE P/2006 VW$_{139}$ FAMILY

3.1 Membership and age from backward integrations

To obtain a preliminary sense of the dynamical stability of asteroids that belong to the group, we calculate their Lyapunov times ($T_{\rm lyap}$) following the methodology described in Milani & Nobili (1992). Our results (see Table 1) show that the orbits of 19 objects can be considered stable ($T_{\rm lyap} > 100$ kyr). Two unstable objects (221660 and 2002 VU$_{137}$) are likely trapped inside the 9J:4A resonance, one (51798) probably interacts with the 20J:9A resonance, and another (32868) appears to be destabilized by the 1J+3S−1A three-body MMR. The asteroid 60320 is located near, but outside the 20J:9A resonance (see Figs. 10 and 11). Its instability may be caused by an unidentified MMR of high order, or it may interact weakly with the

[2] Three-body mean motion resonances are those whose resonant angle is defined as a linear combination of the mean longitudes of two planets and an asteroid (Nesvorný & Morbidelli 1998).

[3] A well-known drawback of the HCM based on the single linkage rule is the so-called 'chaining' phenomenon: first concentrations naturally tend to incorporate nearby groups, thus forming a 'chain' (Zappalà et al. 1994; Everitt et al. 2001).

Table 1. Members of the P/2006 VW_{139} Group

Object	$a_p{}^a$	$e_p{}^b$	$\sin(i_p)^c$	H^d	$p_v \pm \sigma_{p_v}{}^e$	D^f	$T_{\rm lyap}{}^g$	Clustering^h
15156	3.05542	0.1647	0.0437	13.4	0.1032 ± 0.0207	8.7	151.5	Y
32868	3.06753	0.1639	0.0467	14.1	(0.07)	7.5	45.3	U
51798	3.05414	0.1668	0.0451	14.8	(0.07)	5.5	12.0	U
60320	3.05300	0.1602	0.0398	14.8	(0.07)	5.5	91.7	U
117310	3.04833	0.1651	0.0443	14.7	0.0587 ± 0.0084	6.2	3125.0	12%
144767	3.05948	0.1635	0.0464	15.8	0.0770 ± 0.0375	3.3	2325.6	Y
220751	3.04909	0.1608	0.0433	16.6	(0.07)	2.5	1250.0	Y
221660	3.03339	0.1645	0.0374	15.2	(0.07)	4.5	5.4	U
221760	3.04065	0.1621	0.0407	15.8	(0.07)	3.5	3703.7	Y
250710	3.04587	0.1612	0.0378	15.9	(0.07)	3.4	408.2	6%
255251	3.04918	0.1654	0.0463	17.0	(0.07)	2.0	7142.8	Y
255333	3.05631	0.1626	0.0489	15.9	(0.07)	3.3	970.9	0%
257688	3.05167	0.1629	0.0519	15.4	(0.07)	4.2	4166.7	Y
261697	3.05010	0.1637	0.0405	16.5	(0.07)	2.5	699.3	Y
294724	3.06029	0.1625	0.0444	16.8	(0.07)	2.2	1428.6	Y
300163	3.05350	0.1613	0.0379	16.2	(0.07)	2.9	2083.3	Y
305976	3.04891	0.1653	0.0430	16.5	(0.07)	2.6	625.0	0%
2002 VU_{137}	3.02924	0.1627	0.0384	16.9	(0.07)	2.1	4.8	U
2005 TH_{194}	3.05136	0.1611	0.0409	16.6	0.0411 ± 0.0165	3.2	6666.7	0%
2005 YC_{149}	3.05162	0.1613	0.0510	17.5	(0.07)	1.6	4347.8	Y
2007 DP_{70}	3.04943	0.1620	0.0505	16.8	(0.07)	2.2	3333.3	16%
2007 UC_1	3.04305	0.1643	0.0418	16.6	(0.07)	2.4	5555.6	18%
2008 FG_{14}	3.02182	0.1626	0.0364	17.4	(0.07)	1.7	5555.6	Y
2011 UB_{54}	3.03709	0.1625	0.0378	16.6	(0.07)	2.4	800.0	19%

[a] Proper semi-major axis, in a.u.
[b] Proper eccentricity
[c] Sine of proper inclination
[d] Absolute V-band magnitude, from the AstDys website
[e] Geometric V-band albedo, from Masiero et al. (2011) if available; otherwise the mean value for the group is given in brackets
[f] Diameter, in km
[g] Lyapunov time, in kyr
[h] Notes about nature of clustering of secular angles, with "Y" indicating that clustering of secular angles exist, percentage values indicating the chance of clustering derived using clones, and "U" indicating unstable objects

20J:9A resonance. We also note though that Lyapunov time of this asteroid is significantly longer than in the case of other unstable objects. More will be said about dynamical stability in Section 3.3.

The fact that 19 out of 24 objects associated to the group around P/2006 VW_{139} are stable makes it possible to apply the BIM to search for possible clustering of secular angles in the past. As in the analysis of the P/La Sagra cluster presented by Hsieh et al. (2012a), the purpose of the BIM analysis here is two-fold: if suspicious clusterings in the longitude of the ascending node (Ω) and the argument of perihelion (ω) can be found, this analysis would not only allow us to estimate the age of the group, but would also provide support for the hypothesis that these objects share a common physical origin.

As mentioned above, due to the proximity of the group around P/2006 VW_{139} to the Themis family, a distinction between the members of these two groups is very difficult to discern. Therefore, the probability of linking random interlopers with the P/2006 VW_{139} group is much higher than in the case of "typical" families, where the fraction of interlopers is usually below 10 per cent (Migliorini et al. 1995). In some cases though, the fraction of interlopers may be as high as $\sim$25 per cent, as in the case of the Eucharis asteroid family (Novaković, Cellino, & Knežević 2011).

As the members of the group cannot be reliably identified a priori, application of the BIM is complicated because the presence of interlopers could mask possible clustering that would detected if only real members were considered. Given that, we take a slightly unusual approach, where instead of searching for clustering that involves all asteroids linked to the group, we search for clusterings using sub-samples of potential family members. This method allows us not only to estimate the age of the group, but also to characterize the family by distinguishing individual members from interlopers.[4] We name this technique the Selective Backward Integration Method (SBIM).

Specifically, we perform the following four steps:

(i) Starting with the list of dynamically linked group members, as identified by the HCM using the largest cut-off distance ($d_c = 69$ m s^{-1}) for which the group remains separated from Themis family, unstable asteroids are removed, i.e. those with $T_{\rm lyap} < 100$ kyr. This allows us to search for possible clustering among as many asteroids as possible.

(ii) Orbits of stable bodies are numerically integrated using the public domain *ORBIT9* software (Milani & Nobili 1988) embedded in the multi-purpose *OrbFit* package. The dynamical model is purely gravitational and includes four major planets, from Jupiter

[4] A similar idea was proposed by Marcus et al. (2011) to search for families among Kuiper belt objects.

to Neptune, as perturbing bodies. To account for the indirect effect of the inner planets, their masses are added to the mass of the Sun and the barycentric correction is applied to the initial conditions (Milani & Knežević 1992). Orbits of all objects are propagated over 20 Myr in the past. A online digital filtering is applied to the output of numerical integrations in order to remove short periodic perturbations. In this way, mean orbital elements (Knežević & Milani 2000) are obtained, which can then used to search for possible clustering of the secular angles.

(iii) For the 19 stable asteroids in the P/2006 VW_{139} group, we check whether a clustering within 40° in at least one of the secular angles can be found for any sub-group with at least 10 objects. The choice of the limit of 40° is based on previous results obtained in application of the BIM (Nesvorný et al. 2002a; Tsiganis, Knežević, & Varvoglis 2007; Novaković 2010), while the minimum number of objects is chosen assuming a maximum interloper fraction of 50 per cent.

(iv) For each stable object that does not cluster, a set of orbit and "yarko" clones is generated to check whether the orbit uncertainty or the Yarkovsky effect (Bottke et al. 2006) may be the reason why clustering is not observed. In particular, ten orbit clones are drawn from 3-σ interval of the uncertainties of orbital elements listed in Table 2, assuming Gaussian distributions. Then, for each orbit clone, 10 yarko clones uniformly distributed over the interval $\pm(da/dt)_{max}$ are generated, where $(da/dt)_{max}$ is the maximum value of the semi-major axis drift speed due to the Yarkovsky force. Using a model of the Yarkovsky effect (Vokrouhlicky 1998; Vokrouhlický 1999; Vokrouhlický & Farinella 1999), and assuming thermal parameters appropriate for C-type objects (Brož & Vokrouhlický 2008), we estimate the maximum possible drift speed in the proper semi-major axis due to the Yarkovsky thermal effect, for a body of 1 km in diameter, to be $(da/dt)_{max} = 4 \times 10^{-4}$ au/Myr. In this way, a total of 100 clones of each object are produced. The orbits of all clones are numerically integrated in the framework of the same model as nominal orbits, but this time with the Yarkovsky force included in the model.[5] Finally, a possible clustering of the secular angles of each of the clones, and that of the asteroids for which clustering of secular angles is observed in step (iii) is checked. The probability that the stable asteroids whose nominal orbits do not cluster should have exhibited clustering is estimated using the fraction of clones that exhibit clustering.

Applying the above procedure, among 19 asteroids with $T_{\rm lyap} > 100$ kyr, we find a sub-group of 11 objects that exhibit clustering in both Ω and ω about 7.5 Myr in the past. The clustering of Ω is the only prominent one within the last 20 Myr and is very deep (within 32°). As such, we consider it to be a highly reliable event.

On the other hand, although there are several clusterings of ω, none is particularly deep. This, however, is unsurprising, since we expect to find tighter clusterings of Ω than of ω. The reason is that, in the region we consider, the secular frequency[6] gradient $\partial s/\partial a_p$ is more than a factor of two smaller than $\partial(g-s)/\partial a_p$. Thus, small changes in a (e.g., due to the Yarkovsky effect) cause much quicker dispersions of ω in a way that is difficult to follow. Similar situations were seen in the cases of the Veritas, Beagle and Theobalda

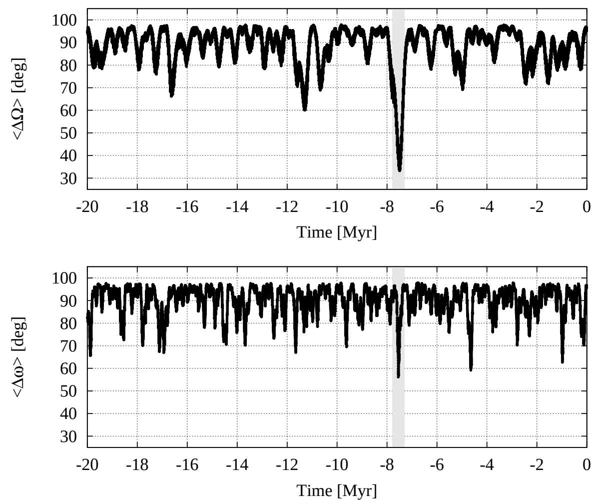

Figure 5. The average of differences in the mean longitudes of the ascending nodes Ω (top), and arguments of perihelion ω (bottom), for 11 dynamically stable asteroids that belong to the P/2006 VW_{139} group. The results are obtained in a purely gravitational model. The most important feature (visible in both angles) is clustering at 7.5 ± 0.3 Myr ago, the likely age of the sub-group.

families (Nesvorný et al. 2002a, 2008; Novaković 2010), for which the use of ω to search for clustering was ultimately impossible.

Due to the aforementioned reasons, the remarkable match found between the deepest clusterings in Ω and ω is a strong indication that they are not the result of random fluctuations, but rather an indication that the objects considered share a common origin. We conclude that this group of 11 asteroids including P/2006 VW_{139} is a real asteroid family formed 7.5 ± 0.3 Myr ago.[7]

The last step in our analysis of clusterings of secular angles is to check whether orbit uncertainty or the Yarkovsky effect could be the reason why several stable asteroids linked to the group by the HCM do not cluster. This is done following the procedure described above in step (iv). The results of this analysis, presented in the last column of Table 1, show that this is unlikely for any of the objects, with probabilities below 20 per cent even in the most promising case of asteroid 2011 UB_{54}. Thus, only 11 asteroids can be reliably associated with the P/2006 VW_{139} family at this time.

3.2 Statistical significance of the new family

An important step in our analysis is to estimate a level of statistical significance of the P/2006 VW_{139} family. Because our conclusion that family is indeed real is mostly based on our findings of the clusterings of secular angles, we tested an hypothesis that these clusterings, simultaneously in both angles, can occur by a chance.

In particular the following test was performed. In the same region as occupied by the P/2006 VW_{139} group, in terms of osculating orbital elements (3.025 $< a <$ 3.075 au, 0.12 $< e <$ 0.21 and 1.0 $< i <$ 4.5°), we generated 2500 uniformly distributed test particles. For these particles we followed more or less the same approach as for the members of the P/2006 VW_{139} group. Their orbits

[5] For simplicity, the Yarkovsky effect is approximated in terms of a pure along-track acceleration, producing the same average semi-major axis drift speed da/dt as expected from theory.
[6] The s, g and $g-s$ are frequencies of longitude of the ascending node (Ω), longitude of perihelion (ϖ) and argument of perihelion (ω) respectively.

[7] We use the phrase "P/2006 VW_{139} group" to refer to the group of 24 asteroids dynamically linked by the HCM, while "the P/2006 VW_{139} family" is used to refer only to those objects whose secular angles (Ω and ω) converge towards the same value.

Table 2. Stable members of the P/2006 VW_{139} group whose secular angles (Ω and ω) do not cluster.

Object	a^a / σ_a	e^b / σ_e	i^c / σ_i	Ω^d / σ_Ω	ω^e / σ_ω	M^f / σ_M
117310	3.0520756061	0.1954589262	3.67207188	89.08283896	297.03599694	162.03649209
	0.0000000861	0.0000001940	0.00001306	0.00024470	0.00024860	0.00003293
250710	3.0406037871	0.1972500111	1.79346026	187.48581675	156.96170804	90.72340929
	0.0000000937	0.0000001605	0.00001632	0.00032530	0.00032990	0.00004392
255333	3.0533298729	0.1298456130	1.53037270	298.13154200	273.37048752	284.24814758
	0.0000001916	0.0000002877	0.00001458	0.00060860	0.00062280	0.00013090
305976	3.0625856084	0.1226730090	1.61519083	215.05214592	343.98604328	221.68737391
	0.0000002950	0.0000001935	0.00001956	0.00054650	0.00055560	0.00009934
2005 TH_{194}	3.0455153624	0.2008262940	1.99615696	191.88575916	172.34882669	110.98328885
	0.0000010430	0.0000043270	0.00003527	0.00067090	0.00288200	0.00169800
2007 DP_{70}	3.0516613516	0.1343786668	3.66093739	145.64448060	346.38036314	4.96950838
	0.0000003648	0.0000005328	0.00004180	0.00043090	0.00055770	0.00028460
2007 UC_1	3.0382721562	0.1874885082	2.62463578	165.94090018	257.24768301	275.35880634
	0.0000004401	0.0000008379	0.00002666	0.00036510	0.00062120	0.00033210
2011 UB_{54}	3.0330485525	0.2025324904	2.51664219	36.42917884	332.62952742	52.94143685
	0.0000000996	0.0000012870	0.00005707	0.00059980	0.00071090	0.00022170

^{a} Osculating semi-major axis and formal uncertainty, in au
^{b} Osculating eccentricity and formal uncertainty
^{c} Osculating inclination and formal uncertainty, in deg
^{d} Osculating longitude of ascending node, in deg
^{e} Osculating argument of perihelion, in deg
^{f} Osculating mean anomaly, in deg

were integrated for 10 Myr and subsequently the Lyapunov times were determined. Then, 1900 test particles on stable orbits were selected and divided in 100 sets (each containing 19 particles). For these sets we checked whether clusterings within 32° and 55°, in Ω and ω respectively, can be found for any smaller subset with 11 objects. The characteristics of requested clusterings as well as the number of objects are the same ones as in the case of the P/2006 VW_{139} family. Also, the fact that test particles are located in the same region of the main belt as the real family members, means that the dynamical conditions are the same, e.g. differential precessions of their secular angles are very similar.

Performing these tests we did not find any appropriate clustering among 100 groups formed by the test particles. A clustering in ω, within 55°, occurs at least once per 10 Myr in about 50 per cent of the cases. However, a clustering in Ω, within 32°, is observed only in a few cases, and none of these were at same time as the clustering in ω. From this line of evidence we concluded that probability to find simultaneous clusterings in Ω and ω for any subgroup of 11 asteroids by the chance is less than 1 per cent. Thus, the statistical significance of the P/2006 VW_{139} family is greater than 99 per cent.

3.3 Physical and dynamical characteristics of P/2006 VW_{139} family

To ascertain the physical characteristics of the members of the P/2006 VW_{139} group, we search for available data about their spectral types and albedos. Unfortunately, little is known about these 24 objects. In particular, none of their spectral types have been determined to date. Geometric V-band albedos, p_V, have been determined for four objects (Table 1), all from WISE observations (Masiero et al. 2011). The average geometric albedo derived from these four values is $p_V = 0.07$. With their low albedos and proximity to the Themis family, most of these objects are likely C-type asteroids. The asteroid 15156 has a somewhat larger albedo than the other three bodies, but considering the uncertainty of this value, its albedo is still within the range expected for C-type asteroids. Spectroscopic observations are encouraged however to definitively confirm the spectral types of the members of the P/2006 VW_{139} family, and characterize the family's level of physical homogeneity.

Next, we examine the dynamical characteristics of the P/2006 VW_{139} group and the surrounding area. The positions of the most important MMRs have been already shown and discussed elsewhere in this paper. To better understand the role of these resonances, and to check whether any connection between the dynamical characteristics of the surrounding area and the apparent structure of the group can be established, we perform the following test: in a box slightly larger ($3.018 - 3.077$ au, $0.11 - 0.22$, and $0.9 - 4.6^\circ$ in osculating semi-major axis, eccentricity, and inclination, respectively) than the one occupied by asteroids from the group, we generate 2000 randomly distributed massless test particles. The orbits of these particles are then numerically integrated for 10 Myr, after which we calculate their synthetic proper elements (Knežević & Milani 2000) and Lyapunov Characteristic Exponents (LCEs).

The results are shown in Figs. 6 and 7, where we show colour coded maps of the obtained LCEs as functions of particle position in proper element space. We note that the figures indicate that most of the region surrounding P/2006 VW_{139} in orbital element space is stable, apart from two strongly chaotic zones centred at about 3.029 and 3.075 au, corresponding to the 9J:4A and 11J:5A MMRs, respectively. Between these two zones, there are also some smaller areas that are weakly unstable. These weak instabilities are caused by higher order MMRs, such as the ones shown in Figs. 10 and 11. Somewhat larger values of the LCEs are also found in the im-

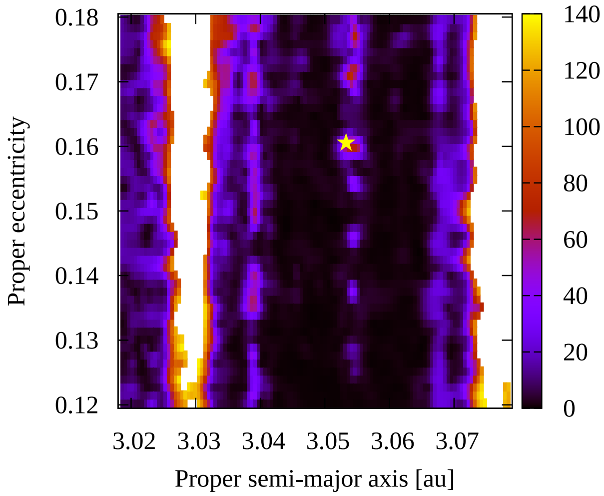

Figure 6. The dynamical structure of the region around P/2006 VW$_{139}$ family. The location of main-belt comet P/2006 VW$_{139}$ is marked by a star symbol. The colour scale indicates Lyapunov Characteristic Exponents (LCEs) (multiplied by 10^6) for 2,000 test particles. The LCEs are inversely proportional to $T_{\rm lyap}$. For example, the value of 100 shown here corresponds to $T_{\rm lyap} = 10$ kyr.

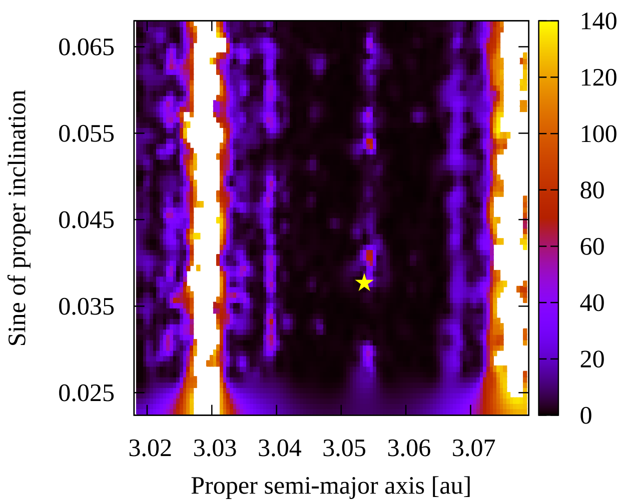

Figure 7. The same as in Fig. 6, but in the (a_p,sin(i_p)) plane.

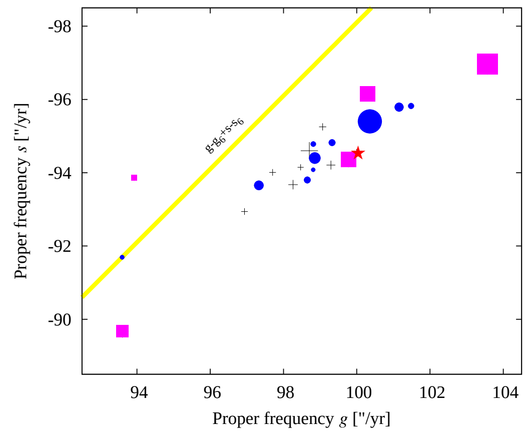

Figure 8. The objects dynamically associated with the P/2006 VW$_{139}$ group plotted in the plane of proper frequency g of the longitude of perihelion *versus* proper frequency s of longitude of the ascending node. As in Figs. 10 and 11 circles represent group members whose secular angles (Ω and ω) cluster, while squares represent unstable objects. The location of main belt comet P/2006 VW$_{139}$ is marked with the star symbol. Sizes of symbols are proportional to the estimated diameters of the corresponding objects. The inclined yellow line indicates the position of the $z_1 = g - g_6 + s - s_6$ secular resonance. The frequencies shown here are calculated according to the synthetic theory (Knežević & Milani 2000).

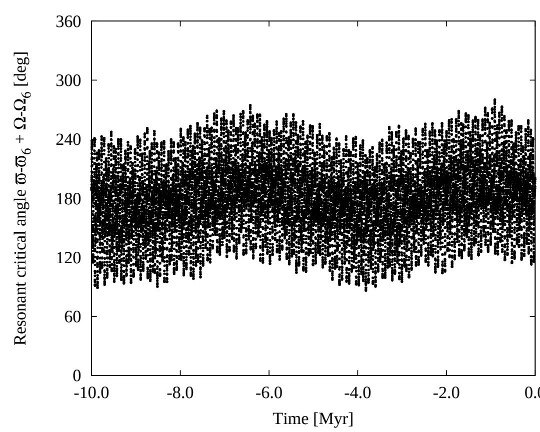

Figure 9. Time evolution of the resonant critical angle $\sigma = \varpi - \varpi_6 + \Omega - \Omega_6$ of the $z_1 = g - g_6 + s - s_6$ secular resonance for asteroid 2008 FG$_{14}$. The critical angle is in an anti-aligned libration state around $180°$ over the complete time period of 10 Myr covered by the integrations.

mediate vicinity of P/2006 VW$_{139}$. These appear to be caused by the 20J:9A and 1J-8S+1A MMRs. However, these resonances are weak and effective only in very narrow ranges of semi-major axis. An illustrative example is P/2006 VW$_{139}$ itself, which is located very close to the 20J:9A resonance, but still does not show any sign of chaotic instability. Thus, we conclude that P/2006 VW$_{139}$ family members are largely stable and unlikely to be significantly dynamically evolved. This conclusion is also valid for the single family member located on the opposite side of the 9J:4A resonance from the other family members, asteroid 2008 FG$_{14}$.

To develop as complete a picture of the dynamical environment as possible, we also search for the presence of secular resonances (up to degree six) in the region. Close to the group, we find only a non-linear secular resonance $z_1 = g - g_6 + s - s_6$ (Milani & Knežević 1992, 1994). Its location is shown in Fig. 8. Most of the objects from the group are far enough to avoid interactions with this resonance. This seems to be also true for asteroid 2002 VU$_{137}$, the only group member located on the other side of the $g - g_6 + s - s_6$ resonance (Fig. 8). However, due to the chaoticity of its orbit caused by the 9J:4A resonance, it is difficult to estimate its secular frequencies, g and s. Therefore, we are unable to draw firm conclusions as to the level of influence of secular resonances on this object. Finally, one family member, asteroid 2008 FG$_{14}$, appears to be inside the $g - g_6 + s - s_6$ secular resonance.

To investigate this possibility, we plot the corresponding resonant critical angle $\sigma = \varpi - \varpi_6 + \Omega - \Omega_6$ in Fig. 9. The behaviour of σ, which oscillates around $180°$, unequivocally confirms that 2008 FG$_{14}$ is locked within the z_1 secular resonance. Because of that, its association to the P/2006 VW$_{139}$ family is less reliable, meaning that it could be an interloper.

In terms of proper semi-major axis, 2008 FG$_{14}$ is located

significantly outside the assumed equivelocity curves shown in Figs. 10 and 11. The usual explanation for this would be Yarkovsky induced drift. However, the P/2006 VW_{139} family seems to be young, and the role of thermal effects is not so obvious. The maximum possible drift speed in proper semi-major axis due to the Yarkovsky effect acting on a 1 km body of $(da/dt)_{max} = 4 \times 10^{-4}$ au/Myr (see Section 3.1) translates into a total drift of 3×10^{-3} au over a period of 7.5 Myr. As Yarkovsky induced drift is inversely proportional to the diameter of the body, for 2008 FG_{14}, it reduces to the maximum value of 1.8×10^{-3} au since the family forming event. This value is almost one order of magnitude smaller than necessary to explain the observed displacement in a_p. The obvious conclusion is that the Yarkovsky effect is not responsible for this object's anomalous displacement in a_p, and that 2008 FG_{14} could be an interloper in the P/2006 VW_{139} family.

Insights into collisional physics may be obtained by analysing the inferred ejection velocity field (EVF) of the fragments (e.g., Cellino et al. 1999). An isotropic EVF can be computed using the well known Gaussian equations. These equations define ellipses in the (a_p,e_p) and (a_p,$\sin(i_p)$) planes, whose shapes and orientations are controlled by two angles, the true anomaly (f) and argument of perihelion (ω) at the epoch of break-up. To connect these two ellipses with real family members, it is necessary to estimate the position of the family's barycentre (i.e., its centre of mass). Then, by adjusting the values of f and ω, and experimenting with different ejection velocity changes (Δv), it is possible to find values of each of these parameters that best correspond to a given family, permitting us to infer some of the properties of the EVF. However, it is well known that asteroid families evolve over time with respect to their original post-impact configurations. They spread and become more dispersed due to chaotic diffusion and gravitational and non-gravitational perturbations (Nesvorný et al. 2002b; Carruba et al. 2003; Dell'Oro et al. 2004; Novaković, Tsiganis, & Knežević 2010). Young families like P/2006 VW_{139}, however, may not have had enough time since their formation to be significantly affected by these effects, meaning that their ejection velocity fields (EVFs) may possibly be reconstructible.

The first step in attempting to reconstruct the P/2006 VW_{139} family's EVF is to estimate a position of the barycentre of the family. In order to do this, the absolute magnitudes (H; Table 1) of the members of the family are converted into diameters, D, using the standard relation (e.g. Bowell et al. 1989)

$$D\ (\mathrm{km}) = 1329\,\frac{10^{\frac{-H}{5}}}{\sqrt{p_v}}.$$

Measured albedos are used for the four objects for which these are available, while the average value of the measured albedos ($p_v = 0.07$) is assumed for all other bodies. Then, assuming the same density for all objects, we estimated their masses, which are then used to derive the position of the barycentre in proper orbital element space. Only the 11 objects classified as real family members are used in this calculation. The obtained barycentre position is at $a_p = 3.05480$ au, $e_p = 0.1644$ and $\sin(i_p) = 0.0431$. The fact that asteroid 2008 FG_{14} may be an interloper has negligible influence on this result.

As asteroid 15156 is the largest member of the family by far, the barycentre position is controlled by its position. As a consequence, the ellipses shown in Figs.10 and 11 are shifted towards larger values of a_p. This may be a result of a notably asymmetric ejection velocity field in terms of semi-major axis, caused by a large transverse velocity component. Such a situation often arises from cratering events (Marzari et al. 1996; Novaković 2010; Vokrouhlický & Nesvorný 2011), though is sometimes observed in the cases of catastrophic fragmentation events as well (Zappalà et al. 1984), although these situations are less likely. To characterise the event which produced the P/2006 VW_{139} family, we estimate the size of the parent body by simply summing up the volumes of all 11 members[8]. These volumes are obtained using the diameters listed in Table 1. Using this method, we calculate a nominal diameter for the parent body of $D_{PB} = 11.1$ km. From this value we estimate the largest remnant to parent body mass ratio M_{LR}/M_{PB} to be 0.83. A realistic value of M_{LR}/M_{PB} is likely somewhat smaller than the value mentioned here because the diameter of the parent body estimated from known family members is a lower limit (Durda et al. 2007). From this evidence, we can therefore conclude that the P/2006 VW_{139} family was not formed in a completely catastrophic fragmentation event. At the moment though, it is not possible to distinguish whether the formation of the family should be classified as a cratering or partially catastrophic event. In any case, the ratio M_{LR}/M_{PB} is high, and may be an explanation for observed asymmetry in the EVF.

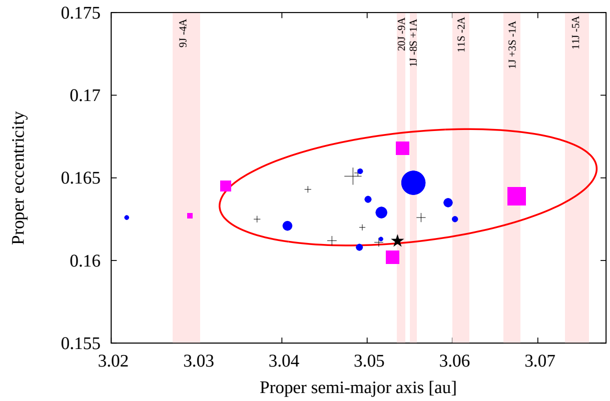

Figure 10. Members of the P/2006 VW_{139} group in the (a_p,e_p) plane. The superimposed ellipse marks an equivelocity curve, computed according to the equations of Gauss (e.g. Morbidelli et al. 1995), for the velocity change of $\Delta v = 60$ m s^{-1}, true anomaly $f = 90°$ and argument of perihelion $\omega = 90°$. Circular symbols represent group members for which Ω and ω cluster about 7.5 Myr in the past, while squares represent unstable objects. Symbol sizes are proportional to the estimated diameters of the bodies plotted. Vertical shaded areas mark the approximate positions of local MMRs. The location of main-belt comet P/2006 VW_{139} is denoted by the star symbol.

Alternatively, the calculated position of the barycentre may be wrong. It may be affected by exclusion of unidentified family members from our calculations. While the chance that any of eight stable asteroids which do not exhibit clustering belong to the P/2006 VW_{139} family is quite small, the status of the five unstable objects remains unclear. Inclusion of these objects in the calculation of the barycentre position moves it to $a_p = 3.05604$ au, $e_p = 0.1642$ and $\sin(i_p) = 0.0437$. In this case, the ejection velocity field becomes even more asymmetric than before. The inclusion of these 5 objects would additionally decrease the M_{LR}/M_{PB} ratio. This would make the explanation that the asymmetry of the EVF is a result of the impact event even less likely. Thus, we believe that at

[8] There are other, generally better, methods to estimate the size of a parent body (Tanga et al. 1999; Durda et al. 2007), but we choose this approach here for simplicity.

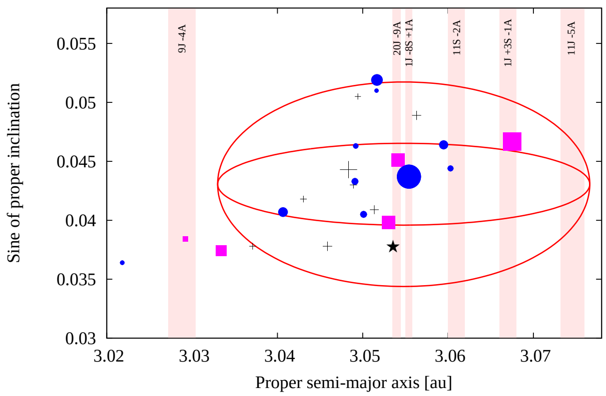

Figure 11. The same as in Fig. 10 but in the (a_p,$\sin(i_p)$) plane. The inner ellipse corresponds to an isotropic velocity field, while the outer one is produce assuming vertical component is 2.5 times larger than other two.

least some of the unstable objects associated to the group by the HCM are not real family members, but we are unable to draw a firm conclusion at this time.

Finally, despite being currently fairly stable, asteroid 15156 could have experienced some small displacement due to chaotic diffusion as it is very close to the slightly chaotic area centred at 3.055 au (Fig. 6). Thus, it may have been less stable in the past, but then evolved onto its current stable orbit due to chaotic diffusion and/or the Yarkovsky effect. Even an exceptionally small amount of Yarkovsky induced drift of the semi-major axis would be enough to drive this asteroid from an unstable to a stable region (or vice versa). The maximum value of $(da)_{15156}$ is about 3×10^{-3} au for 7.5 Myr. Hence, the position of the barycentre might not be fully preserved.

The last characteristic of the EVF that we want to draw attention to is a notably larger spread in the inclination than in the eccentricity (roughly by about a factor of 2). This could not be related to the position of the barycentre. Of course, it could be easily explained by a large vertical velocity component of the EVF (see the two ellipses shown in Fig. 11). Such situations are reported earlier (e.g. Zappalà et al. 1984; Tsiganis, Knežević, & Varvoglis 2007), but to better understand the possible reasons for this, identification of additional family members is necessary. Hence, we postpone this analysis for a future work.

4 SUMMARY AND CONCLUSIONS

If the cluster of asteroids surrounding P/2006 VW$_{139}$ does in fact have a common physical origin, this object would join 133P as the second MBC to be associated with a young collisional family, supporting the hypothesis by Hsieh (2009) that such associations may be necessary for present-day sublimation on main-belt objects to occur. The lack of confirmed young family associations for any other MBCs does not necessarily undermine this hypothesis, as it is possible that many young families remain unidentified due to insufficient numbers of their members simply not yet being discovered, or having insufficiently well-established orbits to perform dynamical linkage analyses. As more asteroids are discovered and orbits of known asteroids are improved by current and next-generation all-sky surveys (e.g. Pan-STARRS), it will be important to continue to search for small clusters of dynamically related asteroids, particularly around known MBCs, that may be previously unidentified young families.

Meanwhile, now that the results of our application of the BIM indicate that the P/2006 VW$_{139}$ group is likely a real asteroid family, it will be beneficial to provide observational confirmation of this dynamical result. Very little information about the spectral characteristics of asteroids belonging to this newly identified family is currently known. As such, we encourage physical characterizations of the members of this family, either photometrically via broadband colours or spectroscopically, to help assess the plausibility of them being physically related in addition to be dynamically related. Furthermore, since family members are expected to share physical properties, the fact that P/2006 VW$_{139}$ has been observed to exhibit cometary activity apparently due to the sublimation of volatile ice (Hsieh et al. 2012b), optical surveys for similar activity among its fellow family members may also be useful in the ongoing search for more MBCs.

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